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NAVY-DEVELOPED LIFE SUPPORT SYSTEMS FOR FULLY ENCLOSED PROTECTIVE SUITS

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INTRODUCTION

The Navy has long had an interest in fully enclosed protective clothing. Early work by the Navy Clothing and Textile Research Unit (NAVYCLOTEXTRSCHU) using forced ventilation in a protective impermeable suit dates back more than 15 years (ref. 1). The Navy research unit is now interested in developing a life support system primarily for shipboard use where many situations exist requiring protection of this kind. For example, engine room environments are often severe, particularly during shutdown periods. Temperatures as high as 140° F are frequently encountered, which when coupled with high humidity preclude the entry of engine room personnel, even to perform such light duties as standing watch. Other shipboard uses include damage control and rescue operations in which personnel may be required to enter spaces filled with smoke or toxic gases.

Previous work at NAVCLOTEXTRSCHU includes the development and testing, under actual shipboard conditions, of an insulated impermeable suit supplied with compressed air for ventilation, cooling, and breathing (ref. 2); the evaluation of a thermoelectric cooled suit (ref. 3); and the physiological evaluation of a liquid air suit (ref. 4).

It was shown that the tolerance time of personnel under elevated temperature conditions can be appreciably extended when compressed air is used. The thermoelectric approach was unsatisfactory because of the weight and bulk of thermoelectric devices available at that time. The liquid air approach, attractive because the liquid air provides cooling, air for breathing, and power for its own circulation, is not generally suitable for shipboard use because liquid air is not usually available aboard ships.

The environmental control unit (ECU), the life support system currently under development by the Navy Clothing and Textile Research Unit, uses wet ice for a coolant. The purpose of this system is to control the environment within a fully enclosed impermeable suit (damage control suit or DCS), also being developed at the Unit's laboratory. The ECU is designed to circulate and cool the air within the suit, remove excess moisture and carbon dioxide, and maintain a safe oxygen level, thus providing maximum personnel protection against hostile environments, such as toxic gases, low oxygen levels, high relative humidities, and temperature extremes.

Although additional work is required on the ECU and modifications are being considered, it appears that the system is well able to fulfill its intended objectives. Tests have shown that a man can be maintained for periods up to 90 min in 130° F environments and for about 2 hr at atmospheric temperatures not greater than 100° F.

The main modification contemplated at this time is a redesign of the ECU to allow it to be carried like a suitcase, rather than worn as a backpack as was originally intended. This change will reduce the bulk of the suit and facilitate entry through the small hatches and passageways found aboard ship, particularly on the smaller vessels. Furthermore, this modification will add

flexibility to the system by allowing either the suit or the ECU component to be used separately as a part of another system if desired.

In another Navy development, the Naval Explosive Ordnance Disposal Facility uses liquid air as a refrigerant in the backpack. Appendix A updates their paper, presented at the 1969 conference on Portable Life Support Systems (ref. 5).

In this report the design and performance of the NAVCLOTEXTRSCHU system are discussed. Data are presented showing the rate of heat absorption under a wide variety of inlet air temperature and relative humidity conditions.

DESCRIPTION OF ECU

There are three basic requirements for the support of a man in a fully enclosed space: (1) temperature control (the removal of excess metabolic heat); (2) oxygen supply; and (3) the removal of carbon dioxide. In the NAVCLOTEXTRSCHU system, as with most life support systems, metabolic heat is dissipated from the man's body by evaporation and conduction into the air within the suit, which must be continually cooled and dried. Several methods for cooling the air are available and have been tried, such as simple circulation of external air, evaporation of liquids, and sublimation of solids. Other methods include thermoelectric cooling and melting of solids, such as plain ice. Each approach has its own advantages and disadvantages, but the wet ice method appears to be most suitable for shipboard use. Wet ice is easily produced and is a desirable refrigerant. It is safe and nontoxic, and pound-for-pound it absorbs as much heat as liquid air (between 0° and 70° F for ice and -314° and 70° F for air).

The ice for the NAVCLOTEXTRSCHU ECU is contained in two finned canisters, each containing 6 lb of ice. Fins formed from deeply corrugated aluminum sheeting are brazed to the four vertical sides of the canisters, as illustrated in figure 5.1, which shows the assembled ECU and its component parts.

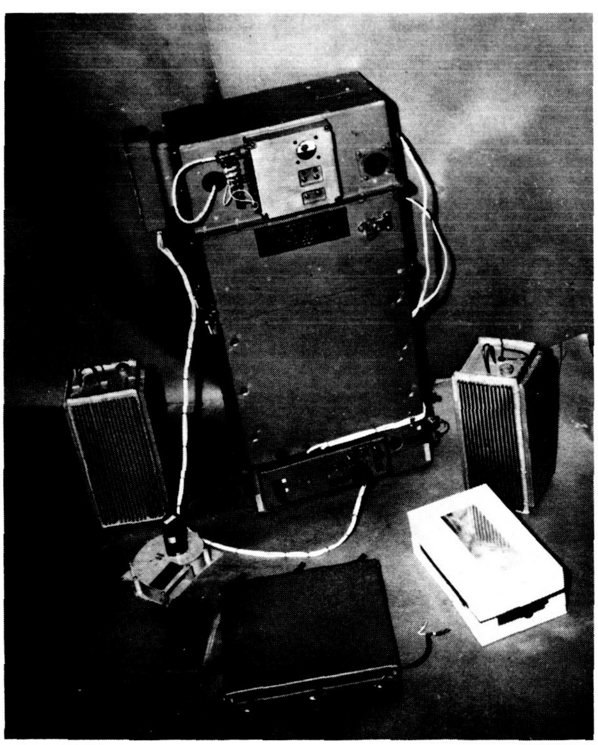

Figure 5.1 *Environmental control unit backpack and component parts.*

The ECU case and the freeze canisters were made by the Frigivest Company under contract to NAVCLOTEXTRSCHU. The case is constructed of PVC plastic with a double outer wall sandwiching 3/8 in. thick polyurethane foam core for insulation. The upper section of the ECU comprising the plenum, contains the blower and the compartment for the chemical pack. It attaches to the lower section with quick-release fasteners to expedite replacement of the freeze canisters. A tank is provided below the freeze canister compartment to contain the condensate. Check valves prevent the condensate from flowing back into the freeze canister compartment should the ECU become inverted. The ECU is designed so that both the cooling canisters and the chemical pack can be quickly and readily replaced when the suit is being used on an extended mission.

The ECU is worn inside a pouch, which is attached to the upper back of the suit (fig. 5.2).

Figure 5.2 *Side view of model 11 prototype damage control suit.*

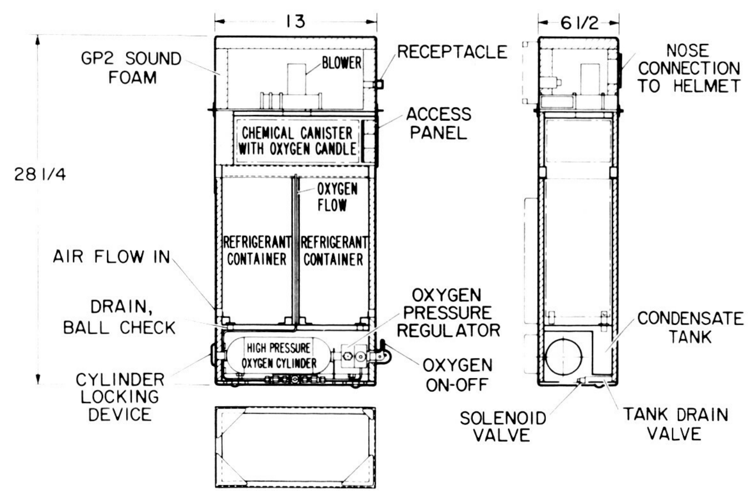

Figure 5.3 *Environmental control unit.*

An aluminum frame support strapped to the wearer supports the backpack as well as the polycarbonate plastic dome helmet.

The approximate overall dimensions of the ECU are 28 X 14 X 18 in. The backpack, fully loaded with ice and chemical packs weighs approximately 40 lb.

Figure 5.3 is a schematic of the backpack. Air enters through the inlet at the lower end of the freeze canisters and passes upwards through the canister fins, giving off heat and moisture as it cools. Passing through the chemical canister, the air gives off additional moisture, oxygen is produced and carbon dioxide is removed. The chemical canister measures 10 in. long, 5-5/8 in. wide and 3-1/2 in. deep. It weighs 4-3/4 lb when filled with lithium hydroxide for the removal of carbon dioxide, and potassium superoxide for the replenishment of the oxygen. The canister bodies are made of stainless steel sheet and contain 12 troughs made from metal screening, 3-1/2 in. deep, running along the length of the canister. The troughs hold the coarsely granular chemicals in layers to allow a free, well-distributed flow of air through the pack. Seven troughs are filled with potassium superoxide for the production of oxygen according to the equation.

$$2\,KO_2 + H_2O \rightarrow 2KOH + 3/2\,O_2 + \textit{heat}$$

The remaining five troughs are filled with lithium hydroxide for the removal of carbon dioxide according to this equation

$$2\,LiOH + CO_2 \rightarrow Li_2CO_3 + H_2O + \textit{heat}$$

Since the moisture in the air greatly exceeds that required for the production of oxygen, a perforated baffle is placed over the side of the chemical pack that contains the potassium superoxide to divert most of the air through the lithium hydroxide. A sodium chlorate candle is incorporated within the chemical pack for emergency use. The candle is fired electrically and produces enough oxygen to support a man for 10 min. Provision was made for an alternate oxygen supply, using oxygen under high pressure from a cylinder below the condensate tank. The alternate system, however, will be eliminated because the chemical system appears to be well able to handle the oxygen requirements. The development, construction and testing of the chemical canisters was done by the MSA Corporation under contract to NAVCLOTEXTRSCHU (ref. 6).

After passing through the chemical pack, the air is drawn into the plenum and exhausted through the outlet into the suit helmet. Air circulation is accomplished by an electrically driven blower made by the Torrington Company. This is a centrifugal-type blower driven by a 12 V Globe dc motor running at about 12,000 rpm. It is designed to produce 27 cu ft of air flow at a head of 3 in. of water. Extensive testing at NAVCLOTEXTRSCHU has shown that it will meet that requirement drawing 2.65 A at 12 V. The blower exhausts into a GP 2 sound foam-lined plenum and, from there, directly into the helmet where the noise level is about 70 dB.

Power is obtained for the system from a 12-V, 10-ah silver-zinc battery (Silvercell) made by the Yardney Company. The battery, which provides ample power for a 2-hr run, weighs only 5 lb including the case, which is attached externally to the ECU with quick-release fasteners. The silver-zinc battery is a low-resistance storage cell that can be discharged up to 30 times its amp-hr capacity rating. Its life is claimed by the manufacturer to be 1 to 2 years after activation, but tests conducted at NAVCLOTEXTRSCHU have indicated a considerably longer life expectancy. Each cell contains a small quantity of an alkaline electrolyte (potassium hydroxide) that is largely absorbed by the plates and separators, resulting in an almost unspillable battery. Charging may be accomplished by an inexpensive, constant potential charger requiring approximately 24 hr for a full charge, from the fully discharged condition.

A novel and highly functional innovation, from a safety standpoint, is the oxygen sensing and warning device shown attached to the backpack in figure 5.1. This instrument, developed by the Beckman Instrument Company, Inc., under contract to the Navy, monitors oxygen from a polargraphic sensor mounted in the plenum and warns the wearer by a red light whenever the oxygen level falls below or rises above safe values. This unit draws very little current (the maximum is about 125 mA). Tests have shown that it responds very quickly to changes in oxygen partial pressure, is essentially insensitive to changes in temperature and relative humidity, and is a highly reliable and apparently nearly maintenance-free device. The entire unit weighs approximately 1 lb.

A low-profile communications headset compatible with existing sound-powered Navy gear has been developed by Dyna-Magnetic Devices, Inc., under contract to NAVCLOTEXTRSCHU, for use with this suit. The headset uses a bone-conduction-type microphone mounted at the rear of the head. All the electronics required for this system are contained within the headset, which weighs approximately 1 lb.

TESTING

Exhaustive tests have been conducted on the backpack to determine airflow rates, cooling rates, and the cooling capacity of the freeze canisters. These tests were held in an environmentally controlled chamber with the use of an "open circuit" configuration (i.e., inlet air was drawn from, but exhausted outside of, the chamber). The outlet air was not allowed to return to the

backpack as it does when the backpack is used with the suit. Testing in this manner allowed accurate control over both inlet temperature and relative humidity. Airflow was measured directly with a hot-wire air-velocity meter (Flowtronic model 55A1). A sensor was mounted in a special flow tube, made and calibrated by Flow Corp., to read directly in ft/min. Exhaust air from the backpack was passed through the flow tube and the flow rate continually monitored. Electrical power for these tests was supplied from a filtered adjustable dc-power supply.

Temperature and relative humidity measurements were made with wet and dry thermocouples. Some difficulty was experienced by the drying out of the wet couples; however, in most tests the humidity was high enough to prevent this happening during the test periods. Signals from the thermocouples were recorded on a multipoint Honeywell temperature recorder.

The rate of water extraction, airflow, and the temperature difference between incoming and outgoing air were used to calculate the rate of heat absorption by the backpack. Since heat absorption rates were generally decreasing and data were taken *at the end* of every 15-min period, conservative values were obtained.

RESULTS AND DISCUSSION

Water versus Sodium Thiosulphate Solution

The finned aluminum canisters used for holding the refrigerant solutions were supplied by the manufacturer filled with 6 lb of a solution reported to be water with 10 percent sodium thiosulphate and 6 percent alcohol added. The use of a frozen salt solution instead of plain ice for cooling purposes has been advocated to take advantage of the negative heat of solution found in some salts and also to lower the temperature of the melting ice and thereby enhance the transfer rate of heat from the air to the canister fins.

The initial tests were conducted on the backpack, with the cooling canisters in place, in a room at 90° F and 65 percent RH. Inlet air was drawn directly into the backpack from the chamber while exhausted air was passed through an instrumented flow tube used for measuring the flow rate. Tests were run using both the salt-alcohol-water solution and plain water frozen in the canisters to determine the relative performance of both liquids.

Results from the tests using the solution-filled canisters showed a very high initial rate of heat absorption but, after about 1 hr, the rate of heat absorption fell to an unacceptably low level though ice remained in the canisters (fig. 5.4). In the tests run with water-filled canisters, on the other hand, the rate of heat absorption, after an initial drop during the first half hour or so, typically increased during the next half hour and thereafter maintained a relatively high level until all of the ice was melted. In these tests the total Btu

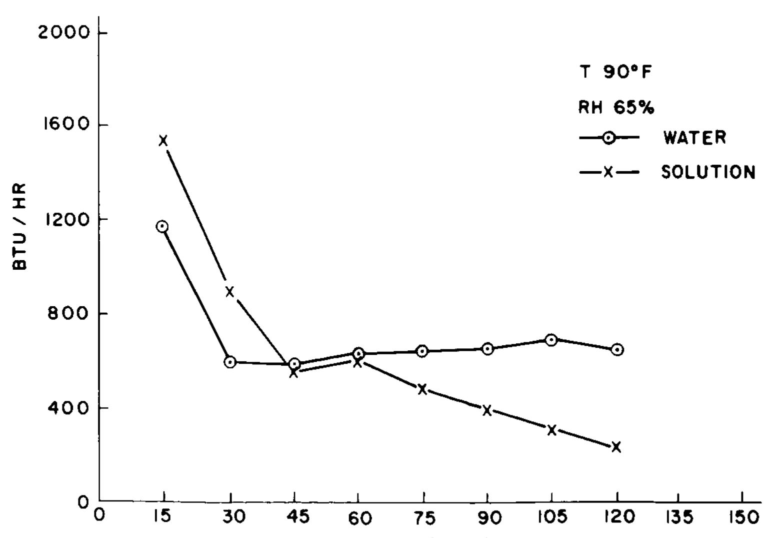

Figure 5.4 *Comparison of heat absorption rates versus time for water and for sodium thiosulphate-alcohol solution in canisters.*

outputs from the water and solution filled canisters did not appear to be materially different and, thus, from a performance point of view, plain ice appeared to be the better choice.

The initial high rate of heat absorption for both the water- and solution-filled canisters apparently occurs before the supercooled ice starts to melt. Once melting begins, the insulation afforded by the layer of water between the ice and the can retards the heat flow. Apparently once this layer becomes thick enough, convection currents form that increase the rate of heat transfer. Hence the recovery noted in the rate of heat absorption in all the tests using plain ice. Melting of the frozen sodium thiosulphate solution, on the other hand, results in the formation of a viscous slush that presumably inhibits convection. Consequently, the rate of heat transfer continues to decline.

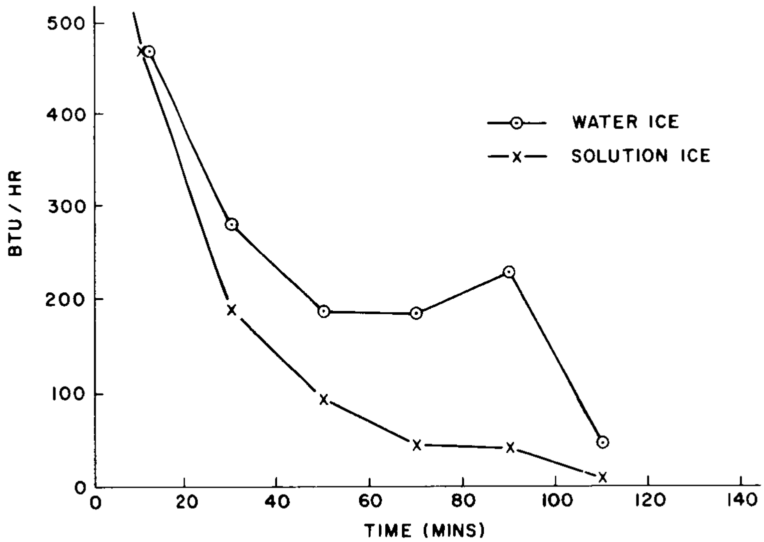

Figure 5.5 *Comparison of heat absorption rates versus time for water and for sodium thiosulphate-alcohol solution in a calorimeter.*

Additional experiments were conducted to investigate further the low rate of heat absorption noted for the solution-filled canisters. A cylindrical aluminum can containing 4 lb of the sodium thiosulphate-alcohol solution was placed in an insulated calorimeter containing 31 lb of water at ambient temperature. Provision was made for continually agitating the water and recording its temperature. The experiment was duplicated using plain-water ice in the can and the results (illustrated in fig. 5.5, where rate of heat loss is plotted against time) confirm the previous findings that heat is more readily absorbed in plain ice than in ice made from the sodium thiosulphate solution. Furthermore, measurements made in a vacuum insulated calorimeter, where ice was melted directly in water, showed that plain-water ice absorbs about 5 percent more heat in melting than ice made from the solution. Thus, since plain-water ice appeared to be an all-around better performer, it was used exclusively for the remainder of the tests.

Effect of Variables on Rate of Heat Extraction

In general, tests were conducted at the relatively high temperatures and humidity levels expected to occur at the outlet of an impermeable suit containing a working man. Test temperatures ranged from 80° to 100° F and relative humidities from 80 to nearly 100 percent. Three rates of air flow through the pack were used (15, 22, and 35 cfm).

Effect of Temperature and RH

The effect of inlet air temperature on the rate of heat absorption is illustrated in figure 5.6. Relative humidity was held at 80 percent for these tests and each data point represents the average of two, and in some cases three, tests; the airflow rate was 35 cfm.

Note that, in general, heat absorption rates are well above the 1000 Btu level that is considered to be the practical minimum required for comfort at the activity levels of interest.

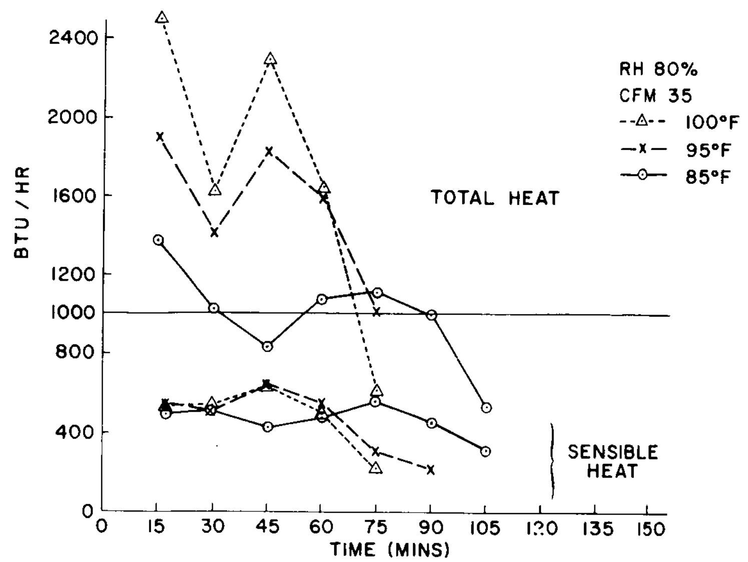

Figure 5.6 *Effect of inlet air temperature on heat absorption rates of canisters in ECU.*

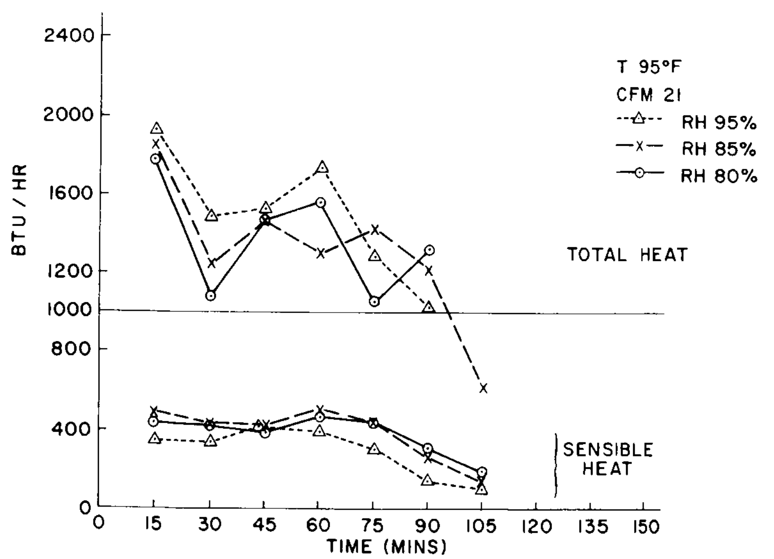

Figure 5.7 *Effect of relative humidity of inlet air on heat absorption rate of canisters in ECU.*

While temperature has a very significant effect on the total rate of heat absorption, its effect on sensible heat extraction (lower set of curves) is almost insignificant.

The effect of relative humidity on heat extraction is shown in figure 5.7 for an airflow of 21 cfm and a temperature of 95° F. The effect on the rate of heat extraction of humidity between 85 and 95 percent is quite small. It is the result of a change of only about 12 percent in water content of the air compared with the almost 60 percent change resulting from the temperature change from 85° to 100° F at 80 percent RH in the previous illustration.

Effect of Rate of Air Flow

In figure 5.8, the effect of the rate of air flow through the backpack on the rate at which heat is extracted is illustrated. The effect, although apparently quite small between 21 and 35 cfm, is to reduce the rate of heat extraction very significantly at 15 cfm.

Several graphs (figs. 5.9 and 5.10) are presented from ref. 6 showing the performance of the chemical pack (breathing canister) under conditions using a simulated man to absorb oxygen and expel carbon dioxide and water vapor. Details covering the development, construction, and testing of the canisters are documented in reference 6. These data demonstrate that, under the conditions of test, the breathing canisters were able to maintain the ambient oxygen level and hold the carbon dioxide level below 0.4 percent.

Tests of the ECU-DCS System

Some tests were run with the ECU attached to a dummy inside the DCS. These tests were run to determine airflow rates within the suit itself and to determine environmental heat loads on the

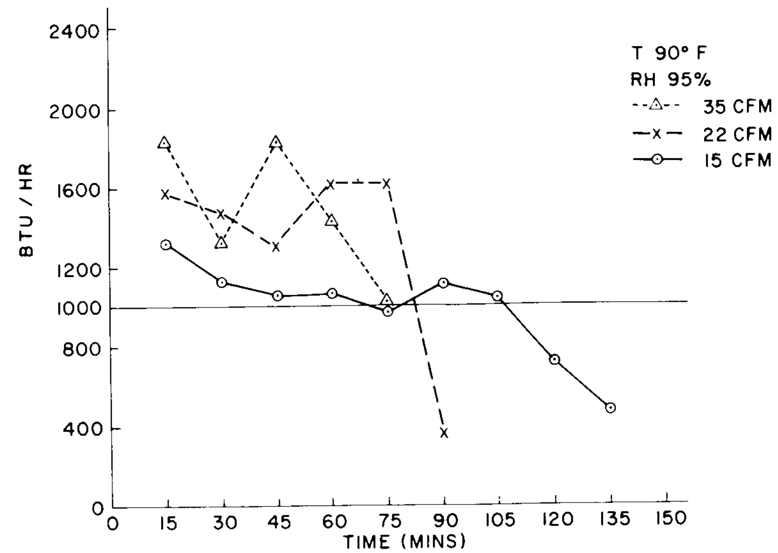

Figure 5.8 *Effect of rate of air flow through ECU on heat absorption rate.*

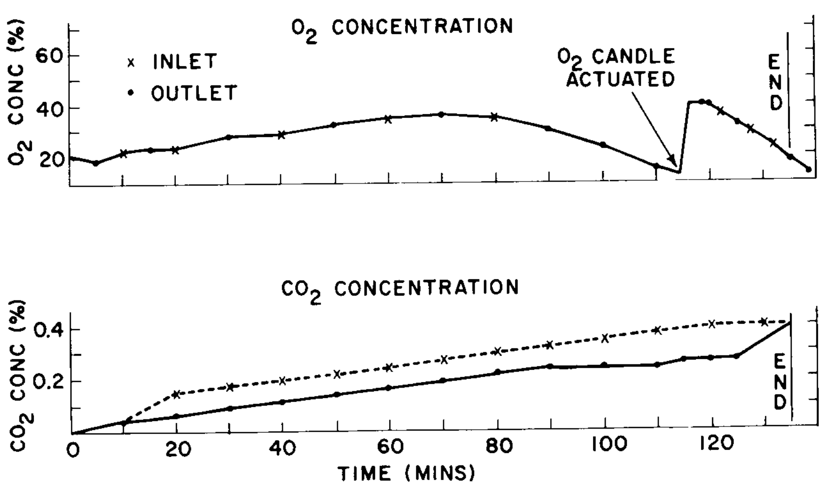

Figure 5.9 *Performance of chemical breathing canister.*

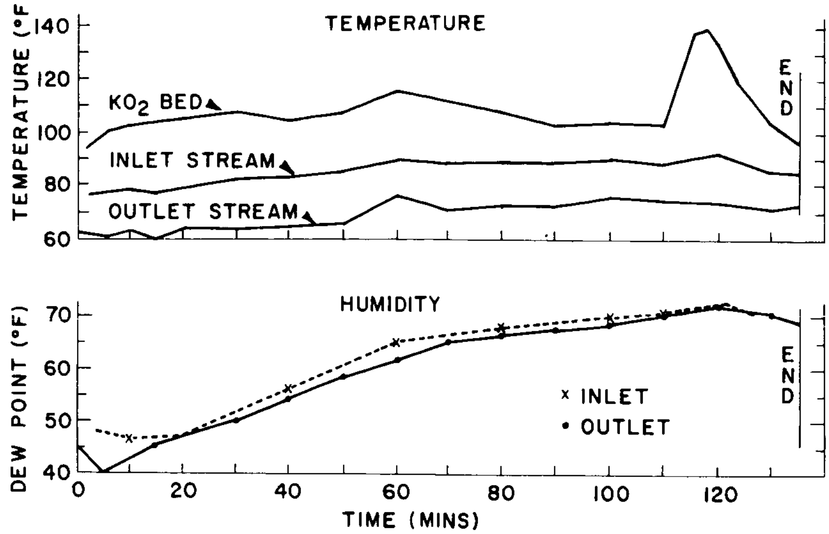

Figure 5.10 *Performance of chemical breathing canister.*

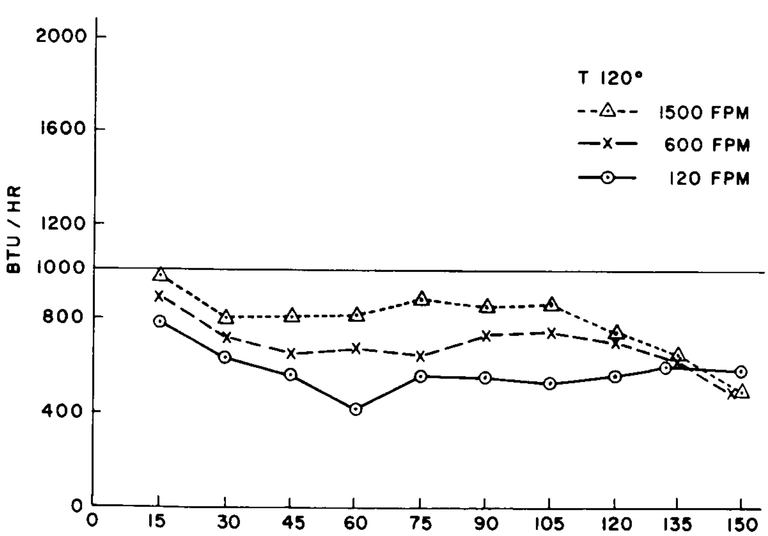

Figure 5.11 *Effect of wind velocity over damage control suit on heat absorbed with dummy in suit.*

ECU for different wind velocities. Figure 5.11 illustrates the effect of wind velocity on the rate at which heat was absorbed through the suit. This heat has to be extracted by the ECU in addition to the heat emanating from the wearer's body and from the chemical pack. Note that, at the test temperature of 120° F in a wind of approximately 1500 ft/min (about 17 mph), approximately 900 Btu/hr of heat absorption was required to balance the heat being conducted through the walls of the suit. The temperature of the air at the outlet of the ECU during this test was in the 70° to 75° F range.

In table 5.1 the effect of external temperature on the heat absorbed through the suit is presented. These tests were run with a dummy inside the suit; thus internal temperatures were much lower than would have been the case had the suit been manned by a live subject. As a result, the values of heat absorbed are presumably unrealistically high. Note that, at 72° F external temperature, 230 Btu/hr were absorbed. If the suit had been manned the net heat flow would probably have been in the opposite direction, resulting in a heat loss instead of in a heat gain. The internal temperature of the suit for this test averaged a little below 60° F.

Table 5.1 *Effect of temperature on heat absorption through DCS (with dummy in suit, wind velocity 120 fpm).*

External temperature, °F	*Heat absorbed by suit, Btu/hr (average for 120 min)*
140	800
120	550
72	230

Manned Tests

Physiological testing of the system is currently being done but data are available at this time from only one manned test of the complete system. This test was conducted in nearly calm air at about 130° F. The subject was seated and was largely inactive. Although this test ran for 105 min, the subject was uncomfortable during the last 15 min. Six thermocouples placed in the suit at various locations showed an average temperature of 88° F after the first 15 min, which gradually rose to just over 99° F at the end of the run. Oxygen, monitored continuously, remained close to the 21 percent level throughout the test period.

CONCLUSION

The objective of this work was to develop an environmental control unit capable of supporting a man in an impermeable suit at ambient temperatures up to 140° F for periods up to 2 hr. The results indicate that these objectives have been largely met, although at high temperature (130° F), cooling is sufficient for about 90 min only. Oxygen production and carbon dioxide scrubbing appear to be adequate. The oxygen level monitoring system works very well and adds a new safety dimension to the system.

Modifications contemplated for the ECU, when funding is available, should make the suit more comfortable to wear and much more practical for use in the confined spaces found aboard ship.

APPENDIX A NAVAL EXPLOSIVE ORDNANCE DISPOSAL FACILITY LIFE SUPPORT SYSTEM

Update on Paper Presented at 1969 Conference on Portable Life Support System.

At the last conference on Portable Life Support Systems, a paper was presented on the modular toxic environmental protective suit (MODTEPS) developed for the Naval Explosive Ordnance Disposal Facility (NAVEODFAC).

Briefly, MODTEPS is a self-contained clothing system designed to protect the wearer from the effects of toxic environments created by the presence of biological or chemical agents. The basic suit operation consists of the evaporation of liquid air contained in a backpack. This air serves to provide both a cooling and a breathing medium. The system is designed so that the internal suit pressure is about 1 in. of water above ambient pressure. This is accomplished by the venting of some of the air to the environment through an exhaust valve. The rest of the air is recirculated to the backpack and aspirated with freshly vaporized liquid air.

As part of the technical evaluation program, a series of tests were performed at the Deseret Test Center, Dugway Proving Ground, Utah. During these tests the suit was subjected to environments contaminated by chemical agents and biological simulant agents.

The chemical agents used were VX, GB, and PS (chloropicrin); VX and GB are nerve agents, while PS is a simulant for some riot control agents.

The test to determine the susceptibility of the suit to GB penetration was conducted in a chamber where the GB concentration could be controlled. Four unmanned suits were placed in the chamber on supports. One suit was placed in an upright position while the other three were bent at the waist, at 30°, 60°, and 90°, respectively. The backpack was placed at low flow rate and the suits were properly inflated. Then 12 g of liquid GB were vaporized on a hot plate. The concentration was 100 mg/m^3. The suits were in this environment for 2 hr. At no time was any presence of GB detected within the suit. The resistance of MODTEPS to VX was determined by placing two suits in a test chamber. One was erect, the other was bent in an arms-extended position. The VX was then showered on the suits to give a contamination of greater than 2 g/m^2. The agent did not enter the suit.

Finally, the suits were subjected to the presence of a biological simulant. This nonpathogenic simulant was BG (Bacillus Globigii) and was present in concentrations of 1.9×10^5 to 3.4×10^5 organisms/liter. Four suits were worn by test subjects and one was placed on a manikin. The subjects changed the backpack on the manikin and performed light exercises for 20 min. The currently used M3 protective suit was also employed in this test. It was found that the MODTEPS provided better protection than the currently used suit against the simulant agent.

From these test results, it was concluded that MODTEPS afforded the wearer adequate protection in areas contaminated by chemical and biological agents.

To provide liquid air for MODTEPS, it was necessary for NAVEODFAC to provide a convenient source of liquid air. It was decided to develop a field portable cryogenerator to manufacture liquid air for use with the suit. A 50-gallon trailer-mounted Dewar will provide a storage and transportation container. Some problem areas have been found in making this unit field-usable.

In the cryogenerator, ambient air is liquefied by being placed in contact with a condenser plate that has been cooled by helium. Moisture is removed from the ambient air by a water and ice separator.

It has been found that on humid days a rapid buildup of moisture subsequently freezes, blocks air flow, and causes the cryogenerator to shut down. Moisture also forms on the condenser, causing production to decrease and eventually cease.

It has also been found that high ambient temperatures inhibit proper heat rejection and cause the unit to overheat and eventually cease operation. A decrease in operating pressure will increase operating time in both these cases; however, the quantity of liquid air produced is lowered. An alternate solution will be investigated.

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